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A REPORT ON THE STATUS OF LINEAR COLLECTIVE ION ACCELERATION WI--ETC(U)
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A REPORT ON THE STATUS OF LINEAR COLLECTIVE ION ACCELERATION WITH INTENSE RELATIVISTIC ELECTRON BEAMS

March 1977

Final Report

Approved for public release; distribution unlimited.

Prepared for
OFFICE OF SCIENTIFIC RESEARCH
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AIR FORCE WEAPONS LABORATORY
Air Force Systems Command
Kirtland Air Force Base, NM 87117

This final report was prepared by the Air Force Weapons Laboratory, Kirtland Air Force Base, New Mexico under Job Order 2301F101. Captain Robert B. Miller (DYS) was the Laboratory Project Officer-in-Charge.

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This report briefly summarizes the state of the art for linear collective acceleration and suggest promising new experiments.

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SECTION I

INTRODUCTION

Because of technological limitations on rf power sources and dielectric breakdown strength, the accelerating electric fields of conventional particle accelerators are generally limited to 10^4 to 10^5 V/cm. As a result, several ion acceleration methods have been suggested (references 1 through 3) which would use the collective fields of an intense relativistic electron beam to accelerate ions to to high energy. In these new schemes, the accelerating fields are not imposed externally, but arise from the collective action of a larger number of particles (electrons) on a smaller number of particles (positive ions). Since the fields in collective accelerators are not limited by electrical breakdown, orders of magnitude increases in the accelerating fields (>10^6 V/cm) should be attainable.

In fact, collective accelerating fields of order 10^6 V/cm have already been demonstrated in experiments in which electrons of a few MeV are injected into a low-pressure, neutral gas (figure 1) (reference 4).

The important results of experiments performed in this configuration at the AFWL can be summarized as follows (references 5 and 6):

1. Ion acceleration occurs only if the peak electron beam current, I_o, exceeds the geometrically determined space charge limiting current, $I_{\ell o}$.
2. Furthermore, as the ratio of $I_o/I_{\ell o}$ is raised above 1 by varying <u>either</u> (L/R) or (R/r_b), the number of accelerated ions increases dramatically as determined from target activation measurements.
3. For high diode impedance beams ($\nu/\gamma \leqslant 0.4$), the accelerated ion spectrum is rather broad, with the spectrum peak occurring at 1.5 E_e, where E_e is the average electron beam kinetic energy. Protons with maximum energies of approximately 3 E_e are obtained. For this parameter range, the observed accelerated ion spectrum is apparently characteristic of the ion spectrum which exists in the initial deep potential well and there is essentially no ion trapping in the secondary moving well.
4. On the other hand, for low impedance beams ($\nu/\gamma \approx 1$) there can apparently be substantial ion trapping in the secondary moving well leading to observed deuteron energies of 11.5 E_e (23 MeV).

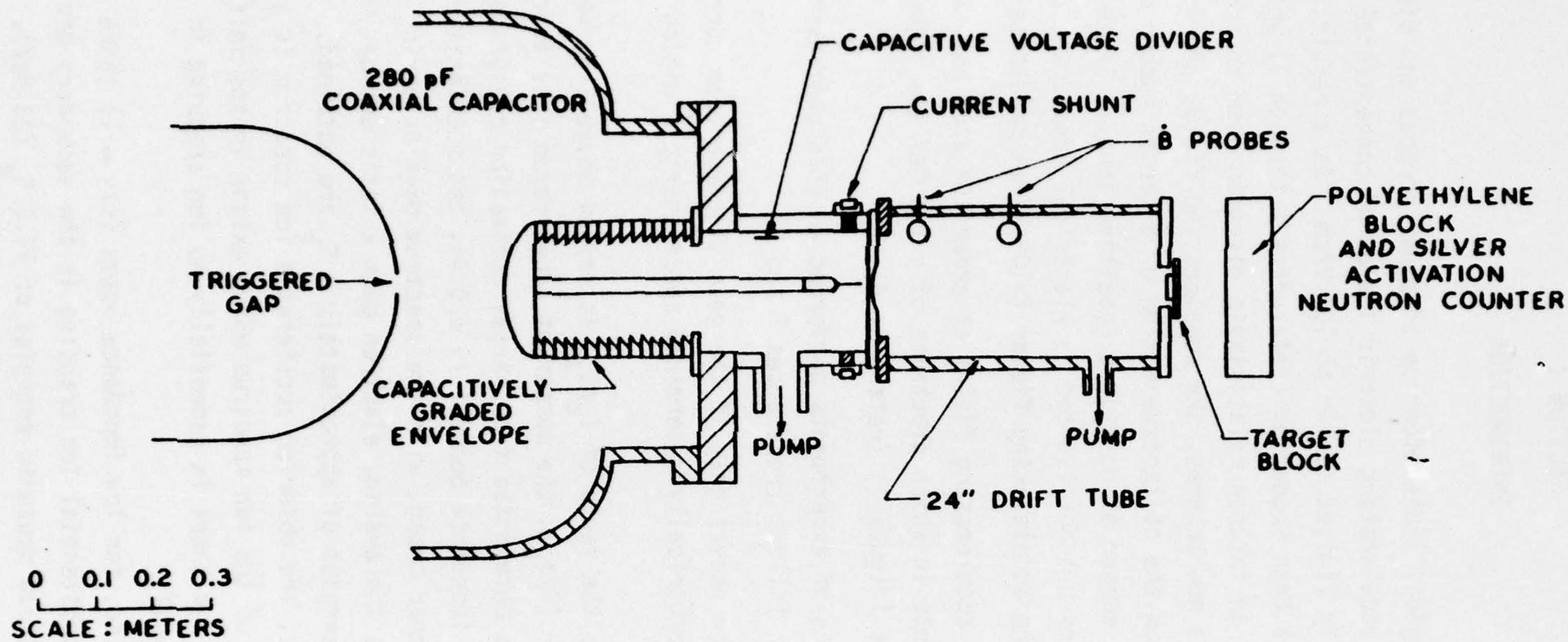

Figure 1. Schematic Description of the Collective Ion Acceleration Experiment.

5. The optimum pressure for ion acceleration is given by approximately one-half the maximum pressure for which a deep well can form.
6. The strength of the accelerating fields is largely determined by the ratio, $I_0/I_{\ell 0}$ which determines the separation distance between the anode and the virtual cathode (accelerating field strengths $\gtrsim 2\times10^5$ V/cm are routinely obtained).
7. The maximum ion beam energy on target represents an energy conversion from electron beam to ion beam of $\leqslant 1\%$.

Although this research has indicated that large collective accelerating fields can be achieved, acceleration of ions in this geometry occurs when the potential well associated with the virtual cathode collapses due to neutralization of the electron space charge through ionization of the background gas. Since net acceleration occurs when the ions become untrapped, the process is largely uncontrolled and does not appear capable of generating large numbers of high energy ions.

A more desirable situation is one in which ions become trapped in a deep potential well and the motion of the well is then controlled to permit ion acceleration over substantial distances. As a result, in recent years several acceleration schemes have been proposed to produce the desired results. These schemes can generally be classified as either wave methods or net electron space charge methods. Examples of the first class include the autoresonant accelerator concept (reference 2) (cyclotron mode) and the Naval Research Laboratory (NRL) scheme using a converging waveguide (reference 3); an example of the second class is the controlled ionization front scheme of Olson (reference 1). In addition, there are several more examples of the second class which could be termed schemes for virtual cathode control (reference 7).

The autoresonant accelerator concept and the NRL space charge wave concept are basically similar although different negative energy modes are used for the traveling wave. In both schemes the maximum well depth available for trapping ions is limited by linearity requirements to $\sim 5\times10^5$ V (some fraction of e-beam kinetic energy). In addition, the available accelerating fields (averaged down the length of the accelerator) are only 10^4 to 10^5 V/cm. Although the argument is oversimplified, the basic reason is that if the frequency of the wave is held constant the increase in wave phase velocity is achieved by increasing the wavelength. Although the depth of the potential well may actually increase somewhat, the variation is bounded by the linearity requirement so that the net effect is a

decrease in accelerating field along the length of the accelerator. Thus, longer acceleration lengths and longer e-beam pulses are required to achieve high ion kinetic energy. Nevertheless, these schemes are interesting because they have the potential for high efficiency as they use a traveling wave rather than a highly localized potential depression. This permits acceleration of a quasi-continuous train of ions throughout a major portion of the e-beam pulse. In addition, both methods require only passive control during the acceleration phase: Divergence of guide tube and magnetic field in one case; in the other, convergence of the guide tube.

The principal advantage of the Olson scheme is the high accelerating field associated with the deep potential well. On the other hand, the optimum efficiency is probably limited to a few percent, and active control is required.

SECTION II

RESULTS OF PREVIOUS EXPERIMENTS

In recent months a new class of collective acceleration schemes has been proposed (reference 7). The basic concept involves creating a single deep potential well (a virtual cathode) and controlling its motion. Before turning to these schemes it is helpful to re-examine some of the previous results pertaining to the time dependent behavior of the diode (reference 8) and to the structure of the accelerating fields in the neutral gas injection experiments (reference 5).

The substantial changes which occur in both the number of accelerated ions and the average ion energy as the ratio $I_0/I_{\ell o}$ is varied are due to changes in the structure of the accelerating fields. In order to study the origin and behavior of the accelerating region, carbon activation was investigated as a function of radial distance from the axis of the drift chamber and longitudinal distance from the anode for two different values of $I_0/I_{\ell o}$. Carbon blocks measuring 2.5x2.5 cm were suspended on nonconducting fibers to minimize field distortions.

The activation results for the case of $I_0/I_{\ell o} = 1.4$ are shown in figure 2. No N^{13} activity was observed when the targets were placed less than 17.5 cm from the anode plane. For larger distances, up to 25 cm, higher activities were noted in the targets farthest from the central axis of the drift tube; while for still larger anode separations, the highest activation occurred on axis. Radially accelerated ions were also observed with carbon blocks situated along the bottom of the drift tube at various distances from the anode plane. These results indicate that the accelerating electric fields for this geometry are largely radial at small distances from the anode, but become predominantly axial in the region 17.5 cm to 28 cm behind the anode.

For the alternate case of $I_0/I_{\ell o} = 2.2$, figure 3, substantial activation occurred as near as 10 cm to the anode and increased dramatically to a distance of 25 cm from the anode. In all trials, maximum activity was observed to occur on axis, indicating that the accelerating fields are predominantly longitudinal. Beyond 25 cm, no further increase in activation was observed suggesting that the accelerating field (0.1 to 0.2 MV/cm) is limited to 25 cm behind the anode plane. Few radially accelerated ions were observed and no activity was noted on carbon targets placed on the anode plane. The activation results for this geometry are

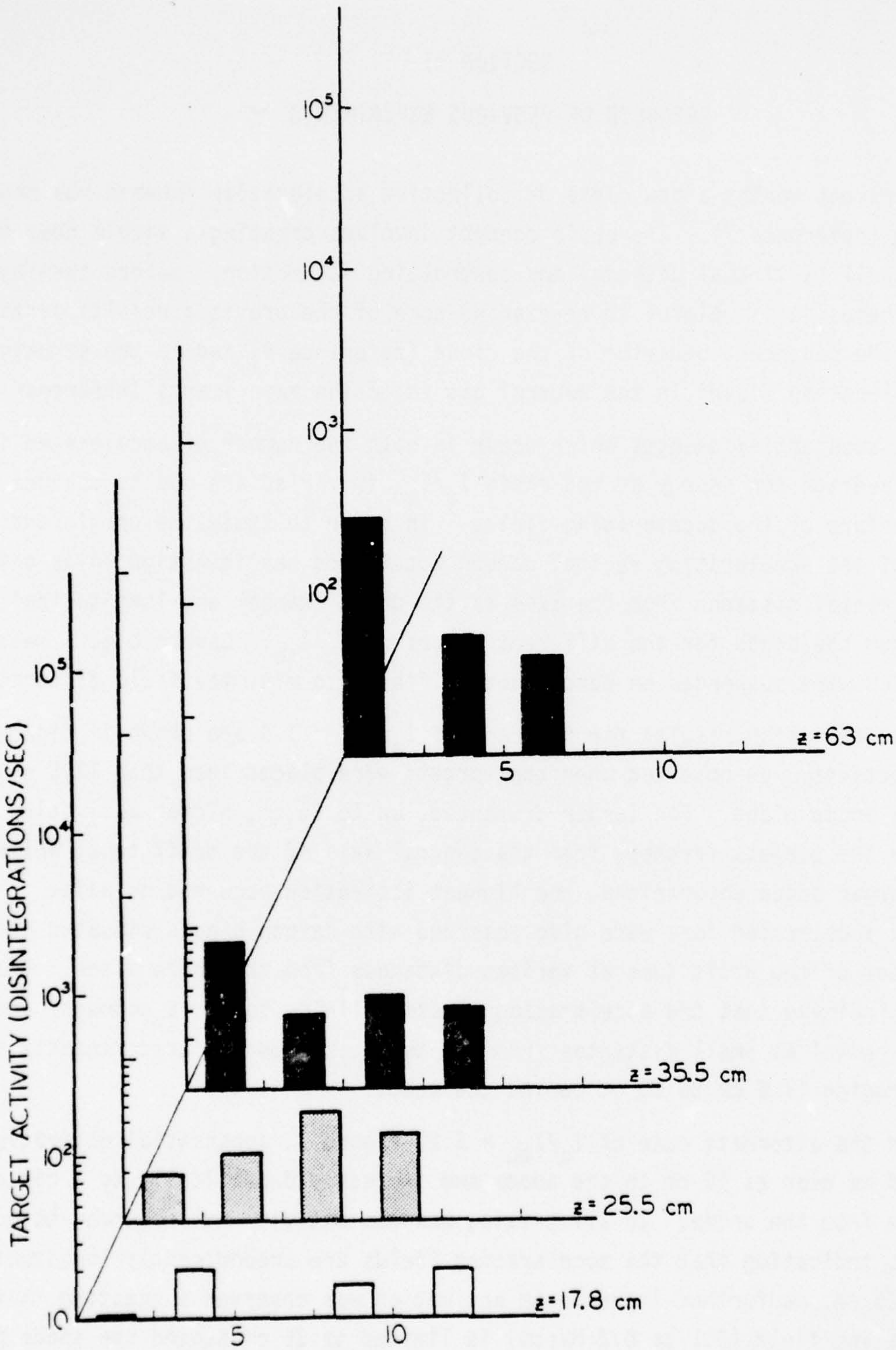

Figure 2. Carbon Target Activation as a Function of Radial Distance From the Axis of the Drift Chamber and Longitudinal Distance From the Anode at 240 mTorr of Deuterium for $I_o/I_{\ell o}$ = 1.4.

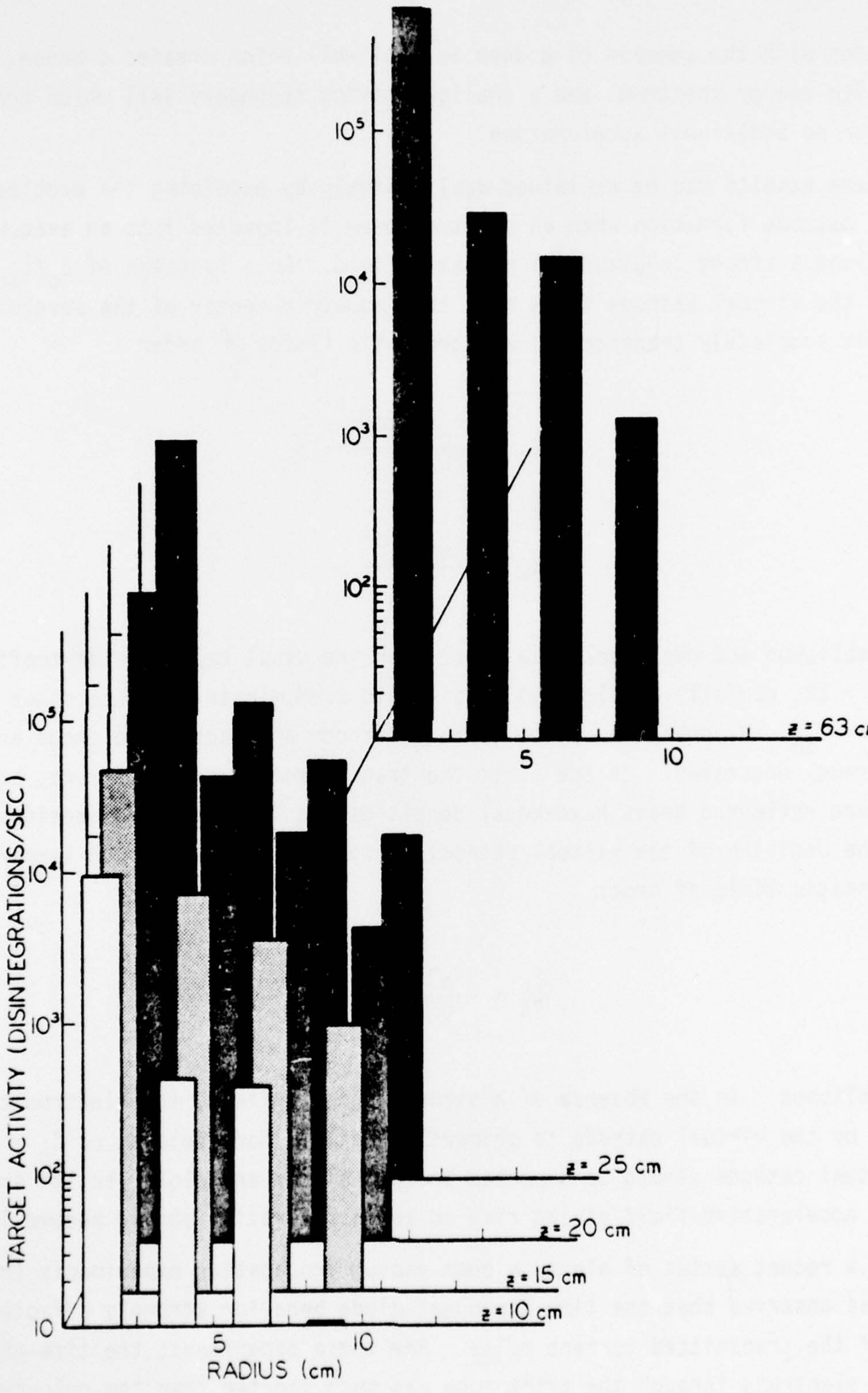

Figure 3. Carbon Target Activation as a Function of Radial Distance From the Axis of the Drift Chamber and Longitudinal Distance From the Anode at 240 mTorr of Deuterium for $I_0/I_{\ell o}$ = 2.2.

consistent with the concept of a deep initial well which creates a broad, accelerated ion energy spectrum, and a shallow, moving secondary well which provides little or no additional acceleration.

These results can be explained qualitatively by examining the problem of virtual cathode formation when an electron beam is injected into an evacuated guide along a strong longitudinal magnetic field. As a function of $I_0/I_{\ell o}$ for $I_0 \gtrsim I_{\ell o}$, the virtual cathode forms near the geometric center of the waveguide and is almost completely transparent; electrostatic fields of order

$$E_z \sim \frac{(\gamma_0 - 1)mc^2}{(L/2)} \qquad (1)$$

$$E_r \sim \frac{(\gamma_0 - 1)mc^2}{R} \qquad (2)$$

are established and can accelerate ions. For the usual experimental configuration, $L > 2R$, radially accelerated ions should predominate. On the other hand, for $I_0 \gg I_{\ell o}$, the position of the virtual cathode approaches the anode and the transparency decreases. In the limit the transparency approaches zero, both injected and reflected beams have equal densities and (in the one-dimensional (1-d) case) the position of the virtual cathode is roughly c/ω_{pb}. A much larger axial electrostatic field of order

$$E_z \sim \frac{(\gamma_0 - 1)mc^2}{c/\omega_{pb}} \qquad (3)$$

is established. In the absence of a strong magnetic field, the electron current emitted by the virtual cathode is primarily radial. Nonetheless, as $I_0 > I_{\ell o}$, the virtual cathode should be expected to form closer and closer to the anode, and the accelerating field giving rise to ion acceleration should become larger.

In a recent series of electron beam vacuum propagation experiments (reference 8) it was observed that the time dependent diode behavior strongly affected the shape of the transmitted current pulse. For these experiments the time-of-flight of beam electrons through the drift tube was much shorter than the relevant time

scale for variations in the beam parameters, and it was expected that the steady-state formulas describing virtual cathode formation and transparency should be approximately valid at each instant of time.

Figure 4 presents a comparison of the corrected diode current pulse and the time dependent space charge limiting current computed from

$$I_{\ell}(t) = \frac{[(\gamma(t)^{2/3} - 1]^{3/2}\, mc^3/e}{1 + 2\, \ln\, (R/r_b)} \tag{4}$$

using $\gamma(t)$ from the corrected diode voltage pulse for two different injection conditions: (1) r_b = 0.635 cm, R = 7.62 cm, B_z = 7.8 kG; (2) r_b = 0.635 cm, R = 7.62 cm, B_z = 3.1 kG. Based on the 1-d calculations of Voronin et al. (reference 9), estimates of the expected transmitted current pulses were made, and these are presented in figure 5 together with the actual transmitted current pulses. Considering the assumptions inherent in the above arguments the agreement is remarkably good, quantitatively as well as qualitatively.

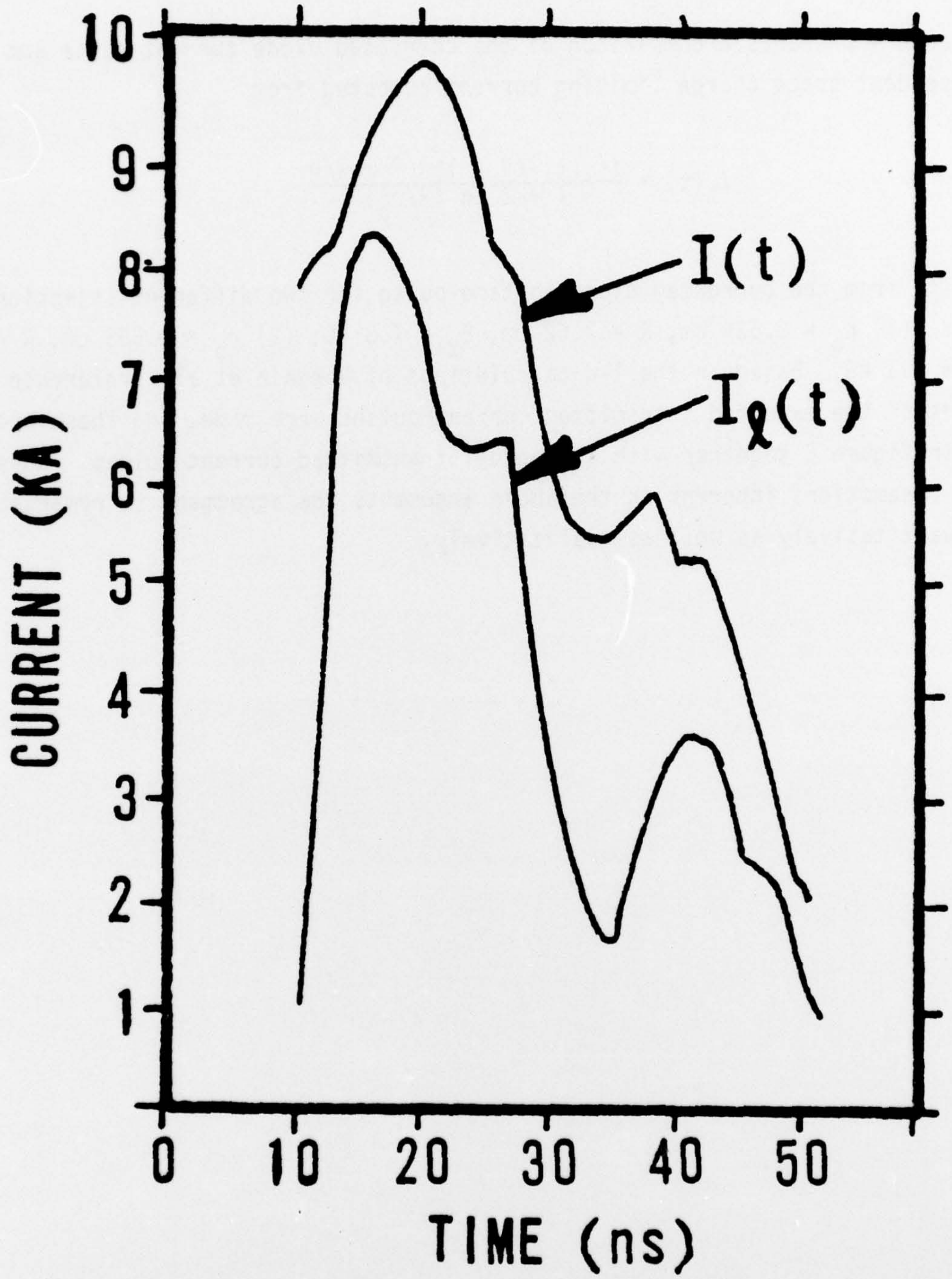

Figure 4. A Comparison of the Corrected Diode Current Probe and the Time Dependent Space Charge Limiting Current. (a) Injection Region I; (b) Injection Region IV.

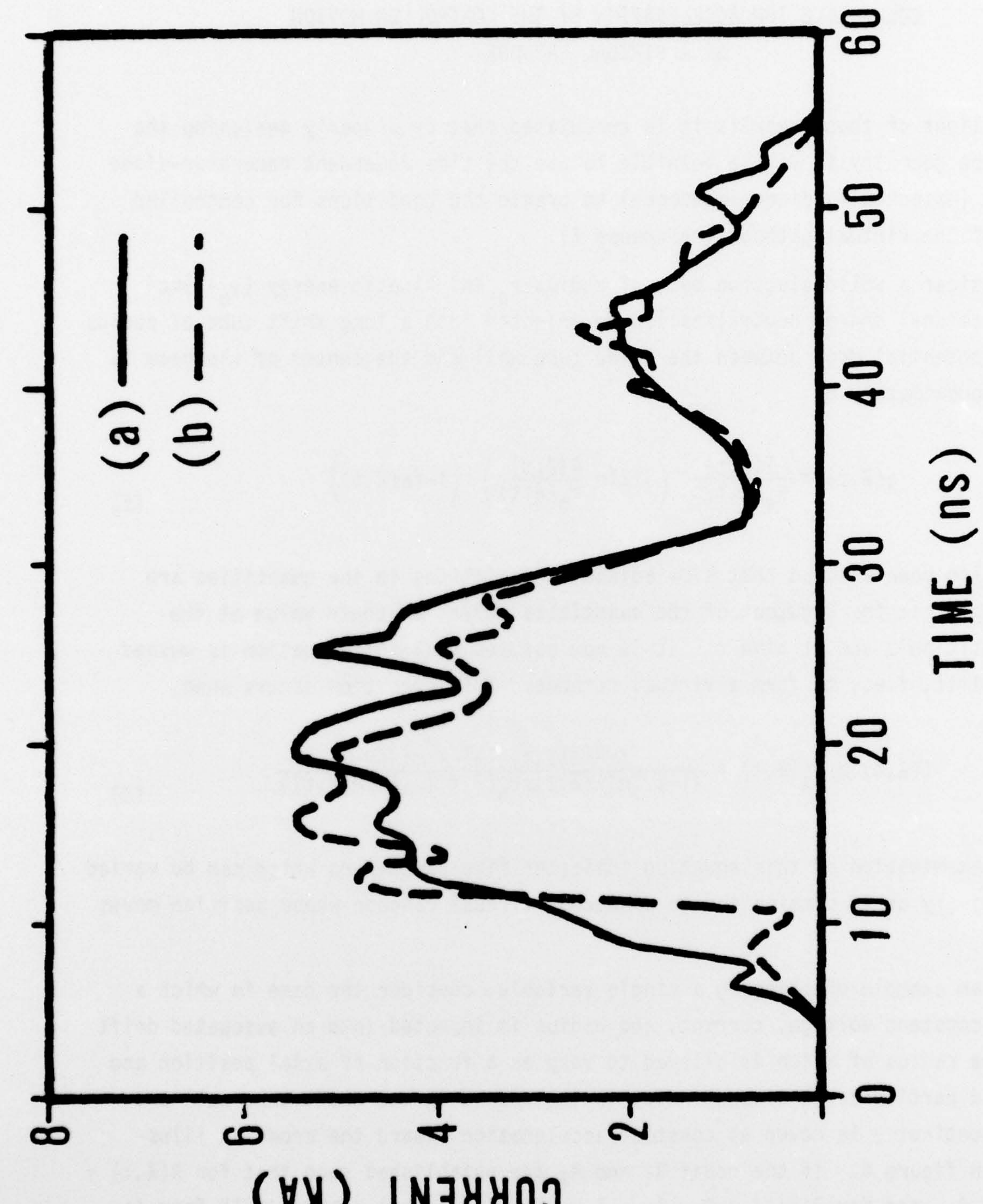

Figure 5. A Comparison of the Estimated and Actual Transmitted Current Pulses. (a) Injection Region I; (b) Injection Region IV.

SECTION III

COLLECTIVE ION ACCELERATION BY THE CONTROLLED MOTION OF A VIRTUAL CATHODE

In light of these results it is speculated that by properly designing the drift tube geometry it may be possible to use the time-dependent generator-diode behavior (essentially diode impedance) to create the conditions for controlled motion of the virtual cathode (reference 7).

Consider a solid electron beam of radius r_b and kinetic energy $(\gamma_0-1)mc^2$ with fractional charge neutralization fe injected into a long drift tube of radius R. The potential drop between the guide tube wall and the center of the beam is given approximately by

$$\phi(z,t) \simeq \frac{I(z,t)}{\beta_e(z,t)c}\left(1+2\ln\frac{R(z,t)}{r_b(z,t)}\right)\left(1-fe(z,t)\right) \tag{5}$$

It has also been assumed that slow adiabatic variations in the quantities are allowed so that the argument of the quantities refers to their value at the axial position z and at time t. It is now assumed that this equation is pushed to its limit, i.e., to form a virtual cathode. This condition occurs when

$$I(z,t) \gtrsim I_\ell(z,t) = \frac{\{\gamma^{2/3}(z,t)-1\}^{3/2}\ mc^3/e}{\{1+2\ \ln[R(z,t)/r_b(z,t)]\}(1-fe(z,t))} \tag{6}$$

An examination of this equation indicates five parameters which can be varied either singly or in combination to produce a virtual cathode whose position moves in time.

As an example of changing a single variable, consider the case in which a beam of constant voltage, current, and radius is injected into an evacuated drift tube, the radius of which is allowed to vary as a function of axial position and time. In particular, a discontinuity is introduced in the drift tube wall and the discontinuity is moved at constant acceleration toward the anode as illustrated in figure 6. If the radii R_1 and R_2 are established such that for $R(z,t) = R_1$, $I_0 < I_{\ell 0}$ and for $R(z,t) = R_2$, $I_0 > I_{\ell 0}$, then a virtual cathode will form in the region of the discontinuity and will propagate toward the anode at constant acceleration. While it would seem difficult to experimentally construct such a

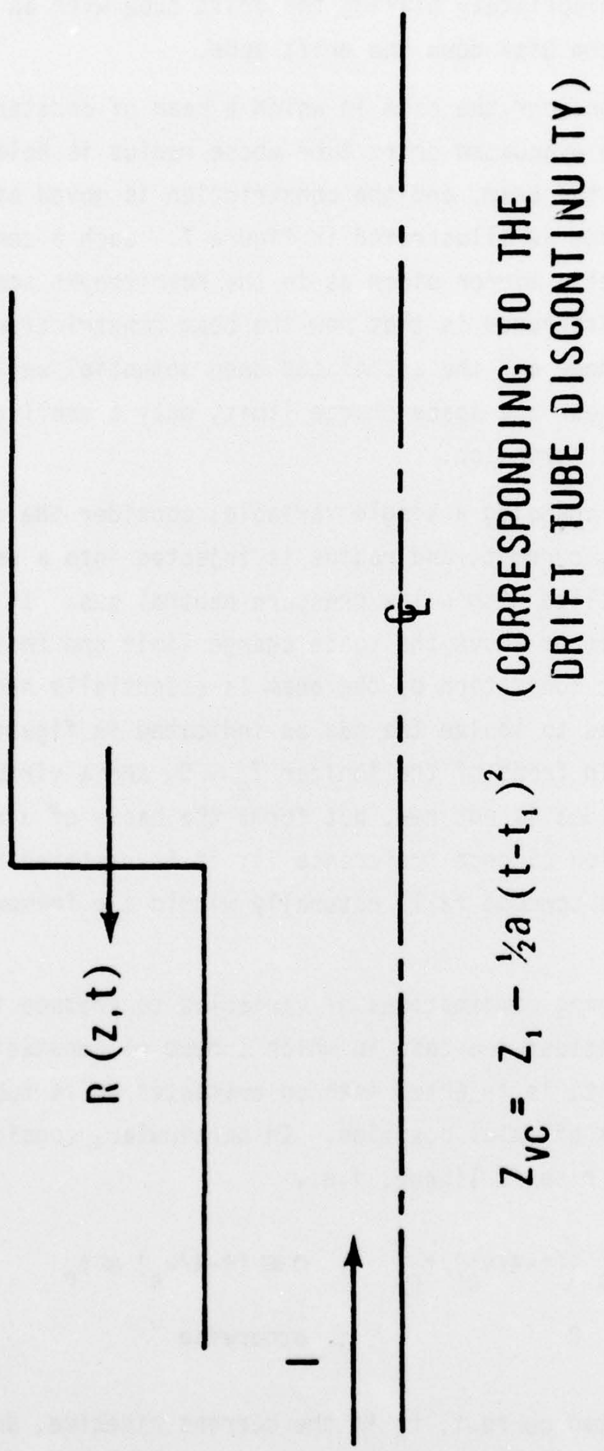

Figure 6. Virtual Cathode Motion With a Propagating Waveguide Discontinuity.

propagating mechanical discontinuity, it may be possible to effectively produce such a configuration by appropriately biasing the drift tube with an electrostatic potential and then moving the bias down the drift tube.

As another example, consider the case in which a beam of constant voltage and current is injected into an evacuated drift tube whose radius is held constant. A constriction is induced in the beam, and the constriction is moved at constant acceleration toward the anode as illustrated in figure 7. Such a constriction could be created by a magnetic mirror pinch as in the Kovrizhnykh accelerator concept (reference 10); the difference is that now the beam constriction results in formation of a virtual cathode and the associated deep potential well. If the electron beam is injected near the space charge limit, only a small constriction can produce virtual cathode formation.

As a final example of changing a single variable, consider the case in which a beam of constant voltage, current, and radius is injected into a drift tube of constant radius which is filled with a low pressure neutral gas. It is assumed that the beam is injected at or above the space charge limit and that the gas pressure is low enough that ionization by the beam is essentially negligible. An external source is then used to ionize the gas as indicated in figure 8. Behind the ionizer $f_e \approx 1$, while in front of the ionizer $f_e \approx 0$, and a virtual cathode is formed. In fact, this idea is not new, but forms the basis of a recently proposed collective acceleration concept (reference 1); it is restated here to merely illustrate that this concept falls naturally within the framework of the present discussion.

As an example of changing combinations of variables to produce the desired virtual cathode motion, consider the case in which a beam of constant voltage and radius, but variable current, is injected into an evacuated drift tube whose radius varies as a function of axial position. In particular, consider the situation in which the current rise is linear, i.e.,

$$
I(z,r) = \begin{cases} I_0 \left((t-z/v_e)/t_r\right) & ; \quad 0 \leq (t-z/v_e) \leq t_r \\ 0 & ; \quad \text{otherwise} \end{cases} \tag{7}
$$

where I_0 is the peak injected current, t_r is the current risetime, and v_e is the electron velocity (assumed constant in z and t for the purpose of this example). The criterion for virtual cathode formation is then given by

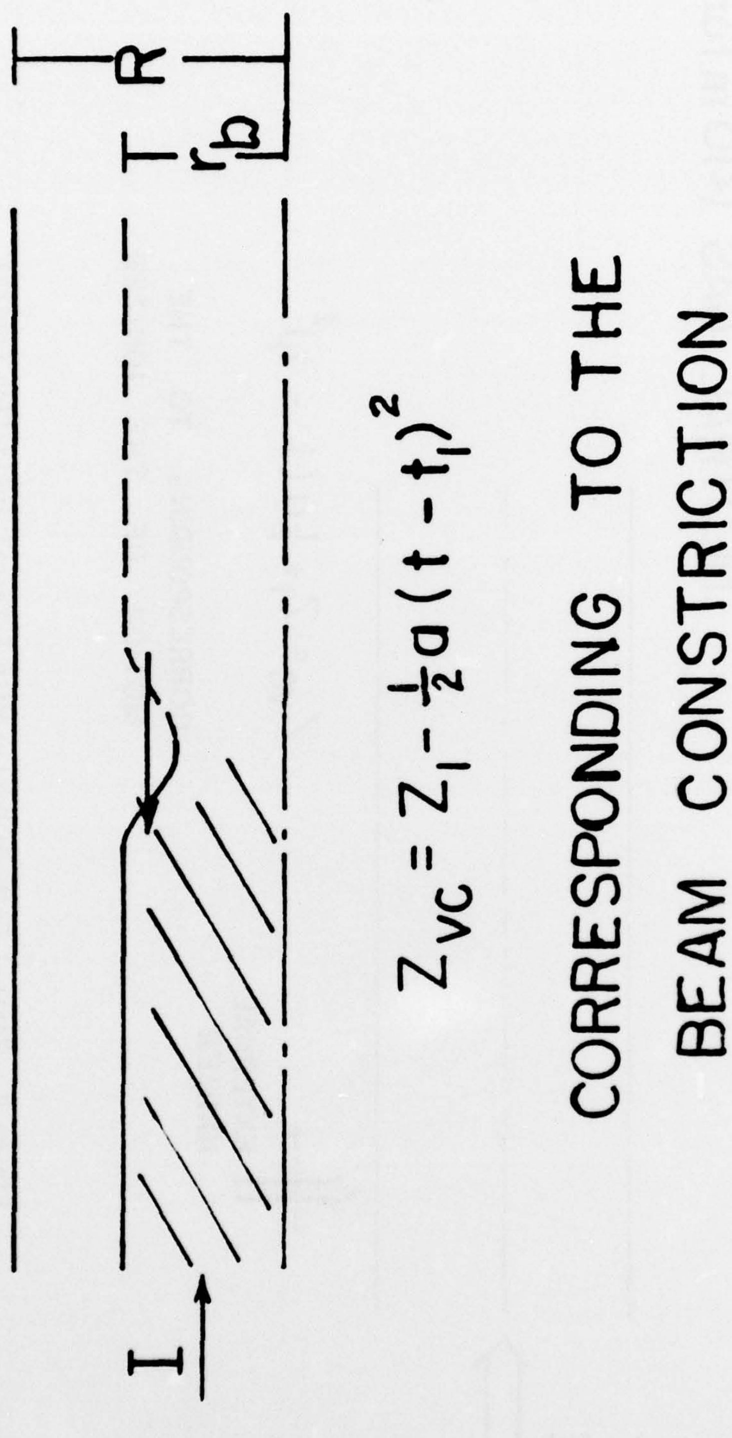

Figure 7. Virtual Cathode Motion With a Propagating Electron Beam Constriction.

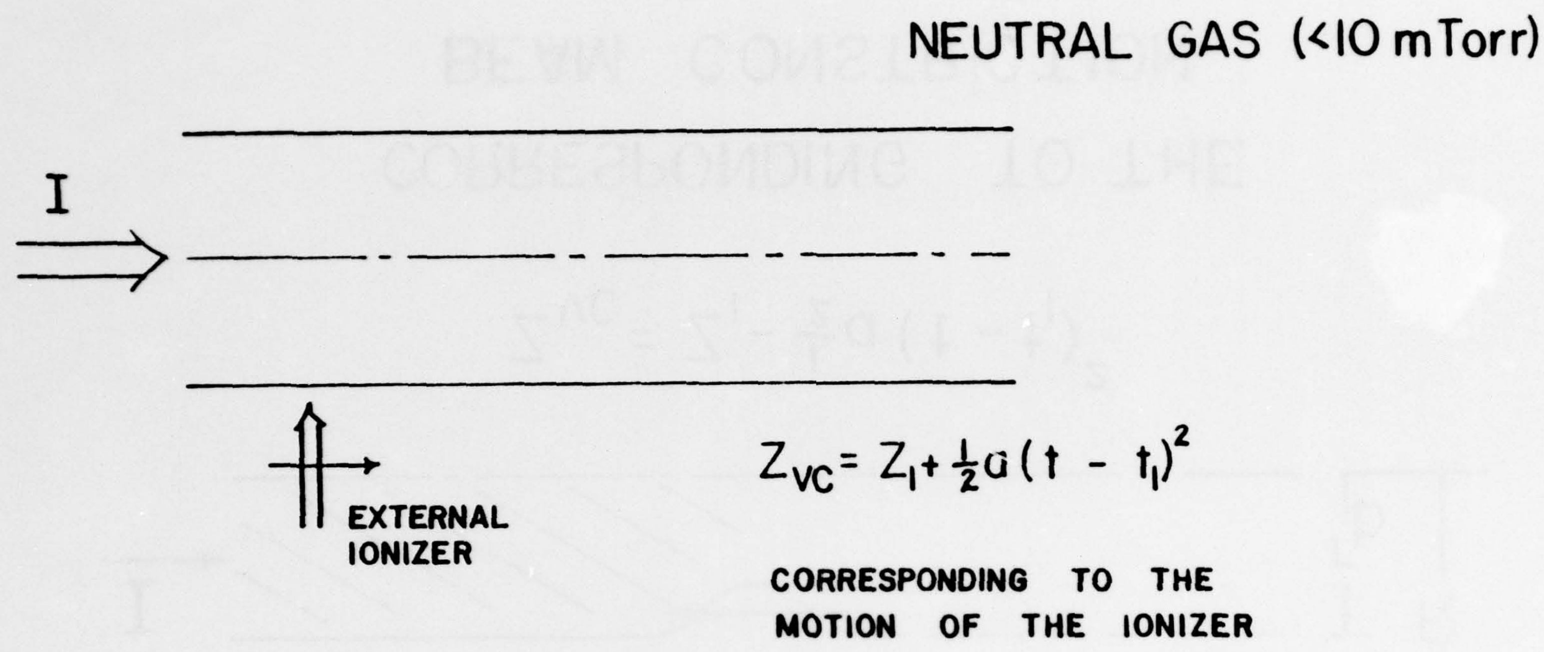

Figure 8. Virtual Cathode Motion With External Ionization Control.

$$I_o\ (t-Zt_r/v_e) \geq \frac{(\gamma_o^{2/3}-1)^{3/2}\ mc^3/e}{1+2\ \ln\ [R(Z)/r_b]} \qquad (8)$$

Defining $I_{\ell o}$, $h(Z)$, and ϕ according to

$$I_{\ell o} = (\gamma_o^{2/3}-1)^{3/2}\ mc^3/e$$

$$h(Z) = \left\{1+2\ \ln\left[R(Z)/r_b\right]\right\}^{-1}$$

$$\alpha = I_{\ell o}/I_o \qquad (9)$$

the criterion may be rewritten as (assuming equality)

$$Z = v_e t - \alpha v_e\ t_r\ h(Z) \qquad (10)$$

which determines the approximate position of the virtual cathode as a function of time for a given axial variation in drift tube radius (through $h(Z)$). Since uniform acceleration of the virtual cathode (toward the anode in this case) is desired, the variation in $h(Z)$ is given by the relation

$$v_e t - \alpha v_e\ t_r\ h(Z) = Z_o - \frac{1}{2}a\ (t-t_o)^2 \qquad (11)$$

where Z_o and t_o (the initial position for the virtual cathode) are related according to

$$Z_o = v_e t_o - \alpha v_e\ t_r\ h(Z_o) \qquad (12)$$

Solution for $h(Z)$ yields the required variation in drift tube radius

$$h(Z) = h(Z_o) + (\alpha v_e t_r)^{-1} \left\{\left[\frac{2v_e^2}{a}(Z_o-Z)\right]^{1/2} + (Z_o-Z)\right\} \qquad (13)$$

An illustration of this concept is presented in figure 9.

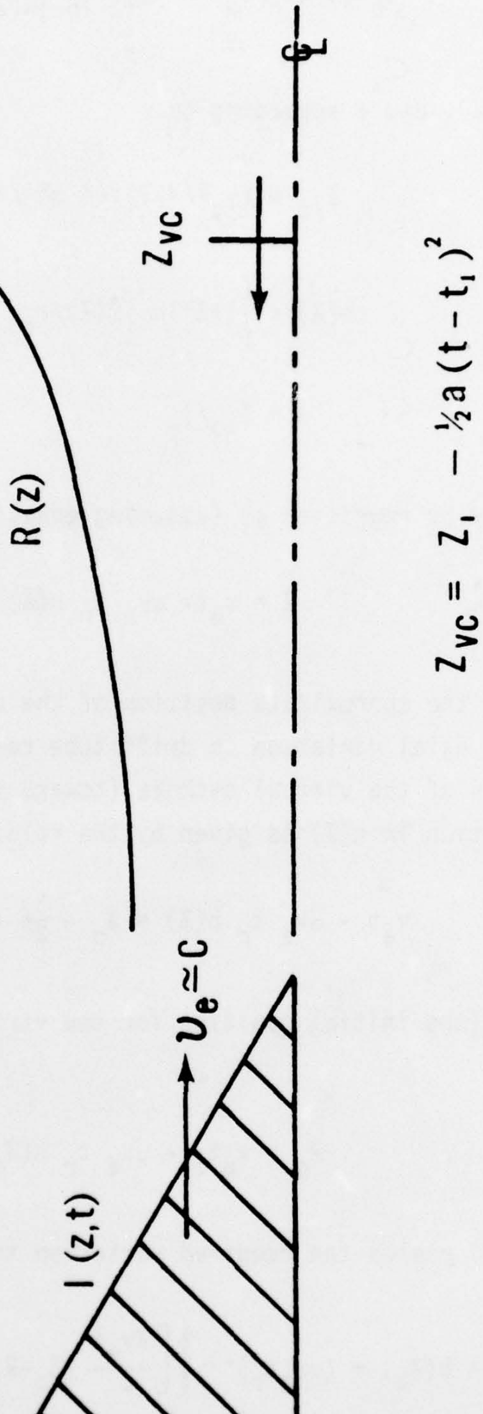

Figure 9. Virtual Cathode Motion Using Time-Dependent Generator-Diode Behavior and a Flaring Waveguide.

As a numerical example for the latter scheme, consider the following set of parameters:

$$R(z_0) = 10\ r_b\ \ (h(z_0) = 0.18)$$

$$R(z_1) = r_b\ \ \ (h(z_1) = 1)$$

$$t_r = 100 \text{ nanoseconds}$$

$$\alpha = 1 \tag{14}$$

It is assumed that the injected beam has an electron kinetic energy of 2 megavolts and a peak beam current of approximately 50 kiloamperes, with a beam radius of the order of 1 centimeter. Consequently, it is expected that accelerating fields of the order of 10^6 V/cm should obtain, which corresponds to a synchronous acceleration of protons in the virtual cathode at the rate of 10^{18} cm/sec^2. Solving for the available acceleration length (z_0-z_1) yields approximately 10 meters which would give 1 GeV protons. Assuming that ion densities of the order of a few percent of the electron density in the virtual cathode can be maintained, kiloampere pulses of subnanosecond duration should be obtained with an electron beam energy to ion beam energy conversion efficiency on the order of 1 percent.

Since the radius of the beam must remain constant, a strong longitudinal magnetic field satisfying the stability condition

$$B_0 > \frac{IR}{5\gamma r_b{}^2} \tag{15}$$

is required, where I is the beam current in kiloamperes, and B_0 is the magnetic field in kilogauss. If this requirement is strongly satisfied, the conditions for the existence of a beam equilibrium are also satisfied. For the example presented above, magnetic fields on the order of 10 kilogauss are required.

Although specific pulse shape has been assumed to illustrate this concept, it must be emphasized that this scheme is much more generally applicable. A common feature of almost all electron beam field emission diodes is a decrease in diode impedance over the pulse time. Consequently, based on the actual time

history of the diode voltage and current traces, a guide tube producing the desired motion of a virtual cathode over at least a portion of the electron beam pulse can be designed for almost every machine of this type.

SECTION IV

CONCLUSIONS AND RECOMMENDATIONS

Much further analysis is required for all the schemes described briefly above, in addition to several other schemes apparent from equation (5), but not considered here. Of particular concern are: (1) the shape of the potential well; (2) the effects of variations in electron beam velocity as the beam nears the virtual cathode region; and (3) the effects of primary electrons reflected from the virtual cathode. Concerning the latter point, Friedman (reference 11) has observed some effects of reflected electrons from a virtual cathode resulting from a discontinuity in the drift tube radius (essentially a stationary version of figure 7. In addition, numerical simulations of this experiment by Godfrey* have indicated a two-stream interaction between injected and reflected electrons, which develops quickly but also saturates quickly.

The latter new scheme is compared with the wave schemes and the ionization front control scheme in table 1 in terms of a few features which might be desired in a collective accelerator. The new scheme should have the large potential well and large accelerating fields; and, in addition, the control of the potential well motion is passive thereby avoiding complicated switching problems. Unfortunately, the new scheme will probably be relatively inefficient.

Table 1

COMPARISON OF WAVE SCHEMES AND GROSS SPACE CHARGE SCHEMES

Desired Features	ARA[a]	CGA[b]	Beam Front Control	Virtual Cathode
Large ϕ (Ion Trapping)	5×10^5 V	5×10^5 V	10^6	10^6
Large E_Z (Accelerator Length)	10^4-10^5 V/cm	10^4-10^5 V/cm	10^6 V/cm	10^6 V/cm
High η ($I\cdot E\cdot\tau$)	10%	10%	0.1-1%	0.1-1%
Simplicity	Passive	Passive	Active	Passive

[a]ARA = Auto-Resonant Accelerator
[b]CGA = Converging Guide Accelerator

*Godfrey, B. B., Private Communication.

Thus, it appears that wave methods of collective acceleration which offer the potential for high efficiency suffer from the disadvantage of smaller well depths and accelerating fields, while net space charge methods which have the deepest potential wells and the larger accelerating fields are inefficient. A possible way of combining the attractive features of both methods is to use a modulated electron beam whose velocity can be controlled in some fashion. Friedman has demonstrated an efficient automodulation process using a cavity structure (reference 12). The modulation offers in some sense the largest wave that can be superimposed on the beams but without the problem of beam self-trapping. The primary problem appears to be an effective method of decreasing the beam velocity so that ions can become trapped in the deep potential wells. Possible techniques include injection through a cusp magnetic field (reference 13) or varying the drift tube geometry to operate near the space charge limit. Such a method (which resembles a modulated electron ring accelerator device) (reference 14) would offer deep wells for ion trapping, the potential for high efficiency, and accelerating fields of a magnitude between those of net space charge methods and wave methods.

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